

# Nonstrange baryonia with the open charm

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The relativistic six-quark amplitudes of the nonstrange baryonia with the open charm are calculated. The poles of these amplitudes determine the masses of baryonia. 9 masses of baryonia are predicted.

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Hadron spectroscopy has always played an important role in the revealing mechanisms underlying the dynamic of strong interactions.

The heavy hadron containing a single heavy quark is particularly interesting. The light degrees of freedom (quarks, antiquarks and gluons) circle around the nearby static heavy quark. Such a system behaves as the QCD analog of familiar hydrogen bound by the electromagnetic interaction.

In Refs. [1, 2] relativistic generalization of the three-body Faddeev equations was obtained in the form of dispersion relations in the pair energy of two interacting quarks. The mass spectrum of  $S$ -wave baryons including  $u$ ,  $d$ ,  $s$  quarks was calculated by a method based on isolating the leading singularities in the amplitude. We searched for the approximate solution of integral three-quark equations by taking into account two-particle and triangle singularities, all the weaker ones being neglected. If we considered such an approximation, which corresponds to taking into account two-body and triangle singularities, and defined all the smooth functions of the subenergy variables (as compared with the singular part of the amplitude) in the middle point of the physical region of Dalitz-plot, then the problem was reduced to the one of solving a system of simple algebraic equations.

In Ref. [3] the relativistic six-quark equations are found in the framework of coupled-channel formalism. The dynamical mixing between the subamplitudes of hexaquark are considered. The six-quark amplitudes of dibaryons are calculated. The poles of these amplitudes determine the masses of dibaryons. We calculated the contribution of six-quark subamplitudes to the hexaquark amplitudes.

In the present paper the six-quark equations for the nonstrange baryonia with the open charm are found. The nonstrange baryonia  $B\bar{B}_c$  are constructed without the mixing of the quarks and antiquarks. The six-quark amplitudes of baryonia are constructed. The relativistic six-quark equations are obtained in the form of the dispersion relations over the two-body subenergy. The approximate solutions of these equations using the method based on the extraction of leading singularities of the amplitude are obtained. The paper is devoted to the calculation results for the baryonia mass spectrum (Table I). In conclusion, the status of the considered model is discussed.

The model in question has only two parameters of previous paper [4]: gluon coupling constant  $g_0 = 0.314$  and cutoff parameter  $\Lambda_q = 11$ . We used the cutoff  $\Lambda_{qc} = 5.18$  which is determined by  $M = 4100 \text{ MeV}$  (the threshold is equal to  $4130 \text{ MeV}$ ).

The quark masses of the model are  $m_q = 495 \text{ MeV}$  and  $m_c = 1655 \text{ MeV}$ . The estimation of theoretical error on the  $S$ -wave hexaquarks masses is  $1 \text{ MeV}$ . This results was obtained by the choice of model parameters.

We consider 9 baryonia with the content  $qqQ\bar{q}\bar{q}\bar{q}$  and the spin-parities  $J^P = 0^-, 1^-, 2^-$ . The isospins are equal to  $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}$  (Table I). We have predicted the masses of baryonia containing  $c$  quark using the coupled-channel formalism. We believe that the prediction for the  $S$ -wave charmed baryonia is based on the relativistic kinematics and dynamics which allow us to take into account the relativistic corrections.

The quark pairs  $Qq$  use there not so many, therefore the baryonium masses cannot increase enough with the decreasing of the cutoff  $\Lambda_{qc}$ .

The degeneration of baryonium masses with the different spin-parities  $J^P = 0^-, 1^-$  was obtained. We cannot also calculate the bound states of baryonia with  $J^P = 3^-$ .

The baryonium state  $\Sigma_c \bar{\Delta} (uuc \bar{d}\bar{d}\bar{d})$  for the spin-parities  $J^P = 0^-, 1^-, 2^-$  is calculated with the nine subamplitudes: seven  $\alpha_1$  (similar to  $\alpha_1^{1uu}$ ) and two  $\alpha_2^{uu1\bar{d}\bar{d}}, \alpha_2^{0uc1\bar{d}\bar{d}}$ .

The baryonium  $\Sigma_c \bar{\Delta} (uuc \bar{u}\bar{d}\bar{d})$  consists of 16 subamplitudes with the spin-parities  $J^P = 0^-, 1^-$ ; 12  $\alpha_1$  and 4  $\alpha_2$ :  $\alpha_1^{1uu1\bar{d}\bar{d}}, \alpha_1^{1uu0\bar{u}\bar{d}}, \alpha_2^{0uc1\bar{d}\bar{d}}, \alpha_2^{0uc0\bar{u}\bar{d}}$ . For the case of the spin-parity  $J^P = 2^-$  the subamplitude  $\alpha_2^{0uc0\bar{u}\bar{d}}$  is absent. The

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TABLE I:  $qqQ\bar{q}\bar{q}\bar{q}$ ,  $q = u, d$ ,  $Q = c$ . Parameters of model: cutoff  $\Lambda = 11.0$ ,  $\Lambda_{qc} = 5.18$ , gluon coupling constant  $g = 0.314$ . Quark masses  $m_q = 495 \text{ MeV}$ ,  $m_c = 1655 \text{ MeV}$ .

Quark content	$I$	$J$	Baryonium	Mass (MeV)
$uuc \bar{u}\bar{u}\bar{u}, ddc \bar{d}\bar{d}\bar{d},$ $uuu \bar{u}\bar{u}\bar{c}, ddd \bar{d}\bar{d}\bar{c};$ $uuc \bar{d}\bar{d}\bar{d}, ddc \bar{u}\bar{u}\bar{u},$ $ddd \bar{u}\bar{u}\bar{c}, uuu \bar{d}\bar{d}\bar{c}$	$\frac{1}{2}; \frac{5}{2}$	0 1 2	$\Sigma_c^* \bar{\Delta}, \Delta \bar{\Sigma}_c^*$ $\Sigma_c \bar{\Delta}, \Delta \bar{\Sigma}_c, \Sigma_c^* \bar{\Delta}, \Delta \bar{\Sigma}_c^*$ $\Sigma_c \bar{\Delta}, \Delta \bar{\Sigma}_c, \Sigma_c^* \bar{\Delta}, \Delta \bar{\Sigma}_c^*$	3305 3293 3303
$uuc \bar{u}\bar{u}\bar{d}, ddc \bar{u}\bar{d}\bar{d},$ $uud \bar{u}\bar{u}\bar{c}, udd \bar{d}\bar{d}\bar{c};$ $uuc \bar{u}\bar{d}\bar{d}, ddc \bar{u}\bar{u}\bar{d},$ $udd \bar{u}\bar{u}\bar{c}, uud \bar{d}\bar{d}\bar{c}$	$\frac{1}{2}; \frac{3}{2}$	0 1 2	$\Sigma_c \bar{N}, N \bar{\Sigma}_c, \Sigma_c^* \bar{\Delta}, \Delta \bar{\Sigma}_c^*$ $\Sigma_c \bar{N}, N \bar{\Sigma}_c, \Sigma_c \bar{\Delta}, \Delta \bar{\Sigma}_c, \Sigma_c^* \bar{N}, N \bar{\Sigma}_c^*, \Sigma_c^* \bar{\Delta}, \Delta \bar{\Sigma}_c^*$ $\Sigma_c \bar{\Delta}, \Delta \bar{\Sigma}_c, \Sigma_c^* \bar{N}, N \bar{\Sigma}_c^*, \Sigma_c^* \bar{\Delta}, \Delta \bar{\Sigma}_c^*$	3317 3316 3329
$udc \bar{u}\bar{u}\bar{u}, udc \bar{d}\bar{d}\bar{d},$ $uuu \bar{u}\bar{d}\bar{c}, ddd \bar{u}\bar{d}\bar{c}$	$\frac{3}{2}$	0 1, 2	$\Sigma_c^* \bar{\Delta}, \Delta \bar{\Sigma}_c^*$ $\Sigma_c \bar{\Delta}, \Delta \bar{\Sigma}_c, \Sigma_c^* \bar{\Delta}, \Delta \bar{\Sigma}_c^*, \Lambda_c \bar{\Delta}, \Delta \bar{\Lambda}_c$	3338 3309
$udc \bar{u}\bar{u}\bar{d}, udc \bar{u}\bar{d}\bar{d},$ $uud \bar{u}\bar{d}\bar{c}, udd \bar{u}\bar{d}\bar{c}$	$\frac{1}{2}$	0 1 2	$\Sigma_c \bar{N}, N \bar{\Sigma}_c, \Lambda_c \bar{N}, N \bar{\Lambda}_c, \Sigma_c^* \bar{\Delta}, \Delta \bar{\Sigma}_c^*$ $\Sigma_c \bar{N}, N \bar{\Sigma}_c, \Sigma_c \bar{\Delta}, \Delta \bar{\Sigma}_c, \Sigma_c^* \bar{N}, N \bar{\Sigma}_c^*,$ $\Sigma_c^* \bar{\Delta}, \Delta \bar{\Sigma}_c^*, \Lambda_c \bar{N}, N \bar{\Lambda}_c, \Lambda_c \bar{\Delta}, \Delta \bar{\Lambda}_c$ $\Sigma_c \bar{\Delta}, \Delta \bar{\Sigma}_c, \Sigma_c^* \bar{N}, N \bar{\Sigma}_c^*, \Sigma_c^* \bar{\Delta}, \Delta \bar{\Sigma}_c^*, \Lambda_c \bar{\Delta}, \Delta \bar{\Lambda}_c$	3331 3331 3361

states with spin-parities  $J^P = 0^-, 1^-, 2^-$  ( $udc \bar{u}\bar{u}\bar{u}$ ) are constructed with 13 subamplitudes: 10  $\alpha_1$  and 3  $\alpha_2$ :  $\alpha_2^{0^{ud}1^{\bar{u}\bar{u}}}$ ,  $\alpha_2^{0^{uc}1^{\bar{u}\bar{u}}}$ ,  $\alpha_2^{0^{dc}1^{\bar{u}\bar{u}}}$ . The baryonium  $udc \bar{u}\bar{u}\bar{d}$  for the spin-parities  $J^P = 0^-, 1^-$  takes into account 23 subamplitudes: 17  $\alpha_1$  and 6  $\alpha_2$ ;  $\alpha_2^{0^{ud}0^{\bar{u}\bar{d}}}$ ,  $\alpha_2^{0^{uc}0^{\bar{u}\bar{d}}}$ ,  $\alpha_2^{0^{dc}0^{\bar{u}\bar{d}}}$ ,  $\alpha_2^{0^{ud}1^{\bar{u}\bar{u}}}$ ,  $\alpha_2^{0^{uc}1^{\bar{u}\bar{u}}}$ ,  $\alpha_2^{0^{dc}1^{\bar{u}\bar{u}}}$ . For the case  $J^P = 2^-$  the subamplitudes  $\alpha_2^{0^{ud}0^{\bar{u}\bar{d}}}$ ,  $\alpha_2^{0^{uc}0^{\bar{u}\bar{d}}}$ ,  $\alpha_2^{0^{dc}0^{\bar{u}\bar{d}}}$  are absent.

The system of equations of the baryonium  $\Sigma_c \bar{\Delta}$  ( $uuc \bar{d}\bar{d}\bar{d}$ ) for the spin-parity  $J^P = 1^-$  (as the example) was constructed:

$$\alpha_1^{1^{uu}} = \lambda + 2\alpha_1^{0^{uc}} I_1(1^{uu}0^{uc}) + 6\alpha_1^{1^{u\bar{d}}} I_1(1^{uu}1^{u\bar{d}}) + 6\alpha_1^{0^{u\bar{d}}} I_1(1^{uu}0^{u\bar{d}}), \quad (1)$$

$$\begin{aligned} \alpha_1^{0^{uc}} &= \lambda + \alpha_1^{1^{uu}} I_1(0^{uc}1^{uu}) + \alpha_1^{0^{uc}} I_1(0^{uc}0^{uc}) + 3\alpha_1^{1^{u\bar{d}}} I_1(0^{uc}1^{u\bar{d}}) + 3\alpha_1^{0^{u\bar{d}}} I_1(0^{uc}0^{u\bar{d}}) \\ &+ 3\alpha_1^{1^{c\bar{d}}} I_1(0^{uc}1^{c\bar{d}}) + 3\alpha_1^{0^{c\bar{d}}} I_1(0^{uc}0^{c\bar{d}}), \end{aligned} \quad (2)$$

$$\begin{aligned} \alpha_1^{1^{\bar{d}\bar{d}}} &= \lambda + 2\alpha_1^{1^{\bar{d}\bar{d}}} I_1(1^{\bar{d}\bar{d}}1^{\bar{d}\bar{d}}) + 4\alpha_1^{1^{u\bar{d}}} I_1(1^{\bar{d}\bar{d}}1^{u\bar{d}}) + 4\alpha_1^{0^{u\bar{d}}} I_1(1^{\bar{d}\bar{d}}0^{u\bar{d}}) + 2\alpha_1^{1^{c\bar{d}}} I_1(1^{\bar{d}\bar{d}}1^{c\bar{d}}) \\ &+ 2\alpha_1^{0^{c\bar{d}}} I_1(1^{\bar{d}\bar{d}}0^{c\bar{d}}), \end{aligned} \quad (3)$$

$$\begin{aligned} \alpha_1^{1^{u\bar{d}}} &= \lambda + \alpha_1^{1^{uu}} I_1(1^{u\bar{d}}1^{uu}) + \alpha_1^{0^{uc}} I_1(1^{u\bar{d}}0^{uc}) + 2\alpha_1^{1^{\bar{d}\bar{d}}} I_1(1^{u\bar{d}}1^{\bar{d}\bar{d}}) + 3\alpha_1^{1^{u\bar{d}}} I_1(1^{u\bar{d}}1^{u\bar{d}}) \\ &+ 3\alpha_1^{0^{u\bar{d}}} I_1(1^{u\bar{d}}0^{u\bar{d}}) + \alpha_1^{1^{c\bar{d}}} I_1(1^{u\bar{d}}1^{c\bar{d}}) + \alpha_1^{0^{c\bar{d}}} I_1(1^{u\bar{d}}0^{c\bar{d}}) + 2\alpha_2^{1^{uu}1^{\bar{d}\bar{d}}} I_2(1^{u\bar{d}}1^{uu}1^{\bar{d}\bar{d}}) \\ &+ 2\alpha_2^{0^{uc}1^{\bar{d}\bar{d}}} I_2(1^{u\bar{d}}0^{uc}1^{\bar{d}\bar{d}}), \end{aligned} \quad (4)$$

$$\begin{aligned} \alpha_1^{0^{u\bar{d}}} &= \lambda + \alpha_1^{1^{uu}} I_1(0^{u\bar{d}}1^{uu}) + \alpha_1^{0^{uc}} I_1(0^{u\bar{d}}0^{uc}) + 2\alpha_1^{1^{\bar{d}\bar{d}}} I_1(0^{u\bar{d}}1^{\bar{d}\bar{d}}) + 3\alpha_1^{1^{u\bar{d}}} I_1(0^{u\bar{d}}1^{u\bar{d}}) \\ &+ 3\alpha_1^{0^{u\bar{d}}} I_1(0^{u\bar{d}}0^{u\bar{d}}) + \alpha_1^{1^{c\bar{d}}} I_1(0^{u\bar{d}}1^{c\bar{d}}) + \alpha_1^{0^{c\bar{d}}} I_1(0^{u\bar{d}}0^{c\bar{d}}) + 2\alpha_2^{1^{uu}1^{\bar{d}\bar{d}}} I_2(0^{u\bar{d}}1^{uu}1^{\bar{d}\bar{d}}) \\ &+ 2\alpha_2^{0^{uc}1^{\bar{d}\bar{d}}} I_2(0^{u\bar{d}}0^{uc}1^{\bar{d}\bar{d}}), \end{aligned} \quad (5)$$

$$\alpha_1^{1^{c\bar{d}}} = \lambda + 2\alpha_1^{1^{\bar{d}\bar{d}}} I_1(1^{c\bar{d}}1^{\bar{d}\bar{d}}) + 2\alpha_1^{1^{u\bar{d}}} I_1(1^{c\bar{d}}1^{u\bar{d}}) + 2\alpha_1^{0^{u\bar{d}}} I_1(1^{c\bar{d}}0^{u\bar{d}}) + 2\alpha_1^{1^{c\bar{d}}} I_1(1^{c\bar{d}}1^{c\bar{d}})$$

$$+ 2\alpha_1^{0^{c\bar{d}}} I_1(1^{c\bar{d}}0^{c\bar{d}}) + 4\alpha_2^{0^{uc}1^{\bar{d}\bar{d}}} I_2(1^{c\bar{d}}0^{uc}1^{\bar{d}\bar{d}}), \quad (6)$$

$$\begin{aligned} \alpha_1^{0^{c\bar{d}}} &= \lambda + 2\alpha_1^{1^{\bar{d}\bar{d}}} I_1(0^{c\bar{d}}1^{\bar{d}\bar{d}}) + 2\alpha_1^{1^{u\bar{d}}} I_1(0^{c\bar{d}}1^{u\bar{d}}) + 2\alpha_1^{0^{u\bar{d}}} I_1(0^{c\bar{d}}0^{u\bar{d}}) + 2\alpha_1^{1^{c\bar{d}}} I_1(0^{c\bar{d}}1^{c\bar{d}}) \\ &+ 2\alpha_1^{0^{c\bar{d}}} I_1(0^{c\bar{d}}0^{c\bar{d}}) + 4\alpha_2^{0^{uc}1^{\bar{d}\bar{d}}} I_2(0^{c\bar{d}}0^{uc}1^{\bar{d}\bar{d}}), \end{aligned} \quad (7)$$

$$\begin{aligned} \alpha_2^{1^{uu}1^{\bar{d}\bar{d}}} &= \lambda + 2\alpha_1^{0^{uc}} I_4(1^{uu}1^{\bar{d}\bar{d}}0^{uc}) + 2\alpha_1^{1^{\bar{d}\bar{d}}} I_4(1^{uu}1^{\bar{d}\bar{d}}1^{\bar{d}\bar{d}}) + 4\alpha_1^{1^{u\bar{d}}} I_3(1^{uu}1^{\bar{d}\bar{d}}1^{u\bar{d}}) \\ &+ 4\alpha_1^{0^{u\bar{d}}} I_3(1^{uu}1^{\bar{d}\bar{d}}0^{u\bar{d}}) + 4\alpha_2^{0^{uc}1^{\bar{d}\bar{d}}} I_6(1^{uu}1^{\bar{d}\bar{d}}0^{uc}1^{\bar{d}\bar{d}}), \end{aligned} \quad (8)$$

$$\begin{aligned} \alpha_2^{0^{uc}1^{\bar{d}\bar{d}}} &= \lambda + \alpha_1^{1^{uu}} I_4(0^{uc}1^{\bar{d}\bar{d}}1^{uu}) + \alpha_1^{0^{uc}} I_4(0^{uc}1^{\bar{d}\bar{d}}0^{uc}) + 2\alpha_1^{1^{\bar{d}\bar{d}}} I_4(1^{\bar{d}\bar{d}}0^{uc}1^{\bar{d}\bar{d}}) \\ &+ 2\alpha_1^{1^{u\bar{d}}} I_3(0^{uc}1^{\bar{d}\bar{d}}1^{u\bar{d}}) + 2\alpha_1^{0^{u\bar{d}}} I_3(0^{uc}1^{\bar{d}\bar{d}}0^{u\bar{d}}) + 2\alpha_1^{1^{c\bar{d}}} I_3(0^{uc}1^{\bar{d}\bar{d}}1^{c\bar{d}}) \\ &+ 2\alpha_1^{0^{c\bar{d}}} I_3(0^{uc}1^{\bar{d}\bar{d}}0^{c\bar{d}}) + 2\alpha_2^{1^{uu}1^{\bar{d}\bar{d}}} I_6(0^{uc}1^{\bar{d}\bar{d}}1^{uu}1^{\bar{d}\bar{d}}) + 2\alpha_2^{0^{uc}1^{\bar{d}\bar{d}}} I_6(0^{uc}1^{\bar{d}\bar{d}}0^{uc}1^{\bar{d}\bar{d}}). \end{aligned} \quad (9)$$

We used the functions  $I_1, I_2, I_3, I_4, I_6$  similar to the paper [3].

The poles of the reduced amplitudes  $\alpha_l$  correspond to the bound states and determine the masses of the charmed baryonia.

In Table I the calculated masses of nonstrange baryonia with the open charm are shown.

We predict the mass of lowest charmed baryonium with the isospin  $I = \frac{1}{2}$  and the spin-parity  $J^P = 1^-$  ( $M = 3293 \text{ MeV}$ ).

The known way with which to calculate the low-energy properties of hadronic systems rigorously is Lattice QCD (LQCD) [5, 6]. In LQCD calculations, the quark and gluon fields are defined on a discretized space-time of finite volume of the lattice volume, such deviation can be systematically removed by reducing the lattice spacing, increasing the lattice volume and extrapolating to the continuum and infinite volume limits using the known dependences determined with effective field theory (EFT) [7–9].

We try to consider the tasks which are similar to the Lattice calculations.

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